EFFECTS OF UNDERGROUND COAL GASIFICATION ON GROUND-WATER QUALITY

J. H. Campbell and V. Dalton

Lawrence Livermore Laboratory
P.O. Box 808, Livermore, CA 94550

J. Busby
United States Geological Survey
Cheyenne, Wyoming

INTRODUCTION

Although in-situ coal gasification offers important environmental advantages when compared with more conventional methods of coal recovery, there are certain environmental concerns that require careful evaluation. The possibility that undergound reaction products may cause adverse changes in ground-water quality is particularly important.

The Lawrence Livermore Labortory (LLL) is pursuing a 3-part program to clarify the nature and significance of the ground-water question. This program includes a laboratory investigation of gasification reaction products and their interaction with coal, a modeling study of the evolving plume of contaminated ground-water, and a ground-water sampling program at the site of an in-situ coal gasification experiment. The gasification experiment was conducted in North-East Wyoming (the Hoe Creek site) by LLL. This paper is focused on the results of our water-sampling program associated with the "Hoe Creek I" gasification experiment and results from recent laboratory experiments on ash leaching and pollutant transport.

The Hoe Creek gasification experiment[1,2] was conducted in the fall of 1976. The gasified coal seam (Felix II) is 25 feet thick and lies at a depth of 125 feet — well below the static water level. The Felix II coal is an aquifer, and is overlain by two additional aquifers. Although the overlying aquifers are also of importance environmentally, this initial study is concentrated on the gasified Felix II seam.

The water-quality investigations have two objectives: First, to determine the effects of in situ coal gasification experiments on the local ground water and second, to learn to predict, reliably, the ground-water effects that may result from commercial-sized gasification operations. It is important to emphasize that the effects of concern may develop over a period of several decades, or even centuries. This is a consequence of the relatively slow transport of contaminant materials through the slow-moving ground-water system. It is, therefore, essential to develop quantitative predictive capabilities based on a thorough understanding of the contaminant source and its chemical and physical evolution. The current water-sampling activities are aimed primary at source definition while the laboratory studies focus on providing data on pollutant leaching and transport.

The water quality field data were obtained principally from a series of wells completed into the Felix II coal and provided with pumps (Fig. 1). The designations EM, DW and OW in Fig. 1 are abbreviations for environmental monitoring well, dewatering well and observation well, respectively.

The curve surrounding the injection and production wells in Fig. 1 shows the estimated extent of coal gasified as deduced from thermocouple data.[1] DW-4 lies within two feet of the gasification boundary and hence provides a close look at the important region just outside the burn zone.

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Figure 2[3] is useful in interpreting the water-quality data obtained at Hoe Creek. In agreement with this model of the undergound source, a variety of inorganic materials have been found issuing from within the burn boundary and a high level of organics (particularly phenolic material) that appears to be concentrated in a thin ring that surrounds the burn zone.

EXPERIMENTAL

Details of the well pumping and sampling procedures used in the field are given elsewhere[4]. Water samples that were to be further analyzed in the laboratory were preserved using well known methods[5,6]. Water samples for field measurements were immediately refrigerated and usually analyzed within an hour of sampling. Methods and procedures used for analyses of the samples are found in references 5-8.

Details of the apparatus, procedure and analysis methods for both the ash leaching and pollutant transport experiments are given in reference 9. A schematic of the coal column apparatus used for the pollutant transport experiments is shown in Figure 3.

RESULTS AND DISCUSSION

A. Field Measurements

Pregasification (baseline data)

Prior to gasification, water from wells in the Felix II coal seam and in the overburden were sampled to provide baseline data with which to compare gasification and post-gasification water analyses. The results of the baseline data for the Felix II coal seam are presented in Table 1. Note that the principal cations are calcium, magnesium, potassium and sodium; the anions are bicarbonate, sulfate and chloride. On an equivalent basis, these seven species balance (i.e., form an electrically neutral solution) to within 3%.

The concentration of phenolic material present before gasification is in the range 0-2 ppb, and the dissolved organic carbon (DOC) is between 3 and 8.5 ppm. Fractionation of the DOC gives an approximately 50/50 distribution between hydrophobic and hydrophilic compounds. Results from further fractionation of the DOC into acid, base, and neutral compounds are discussed in refs. 4 and 10.

Qualitative GC-MS data for the volatile organic species in the water (pre-gasification) show the presence of trace amounts of low-molecular-weight chain hydrocarbons (C_4-C_{12}) as well as simple aromatics such as benzene, toluene and xylenes[8,10].

The amount of methane dissolved in the coal seam water was approximately 11 ± 4 mg/l, pre-gasification. As might be expected, this value was relatively high since coal seams often naturally contain large quantities of free-methane. Water from local ranch wells, which are not completed into the coal seam, contained undetectable amounts of methane (<0.2 mg/l).

Gasification

Although the major emphasis of this study is on the evaluation of the post-gasification ground-water contaminant source, we also analyzed water from several of the monitoring wells <u>during</u> the gasification process. These data provided an estimate of the rate of contaminant buildup in the coal which surrounds the gasifier, as well as the approximate areal extent of the contamination as a function of time.

TABLE 1

Results of water analyses before, during, and after the Hoe Creek I experiment. The baseline data represent an average of analyses from 7 wells completed into the Felix II coal seam. Only "during" and "after" data for EM-1 (100 ft from burn boundary) and DW-1 (10 ft from burn boundary) are shown here since they typify the general trends observed with increasing radial distance. Also given are post-gasification data for inside the burn boundary. Data for 182 and 280 days following gasification and complete data for all other wells are summarized elsewhere[10].

Species	Conc. Units	Pre-Gasif. Baseline Data[a]	Inside Burn Boundary (Injection Well) Post-Gasif. 83d	Outside Burn Boundary DW-1 (10 ft.) During Gasif.	DW-1 (10 ft.) Post Gasif. 3d	DW-1 (10 ft.) Post Gasif. 83d	EM-1 (100 ft.) During Gasif.	EM-1 (100 ft.) Post Gasif. 3d	EM-1 (100 ft.) Post Gasif. 83d
Alkal.	mg/l	407 ± 30	63	595	693	430	837	686	636
Al^{+3}	µg/l	0 - 10	220	0	10	20	0	10	10
As^{+3}	µg/l	0 - 1	8	1	1	0	0	0	1
Ba^{+2}	µg/l	100 ± 100	0	200	600	0	0	0	1
HCO_3^-	mg/l	496 ± 40	0	725	845	524	1020	836	776
B^{+3}	µg/l	86 ± 30	710	90	110	360	90	90	70
Br^-	mg/l	0 - 0.1	1.0	0.2	0.3	0.7	0.0	0.1	0.1
Cd^{+2}	µg/l	0	0	0	0	0	1	0	1
Ca^{+2}	mg/l	36 ± 10	570	35	110	220	110	100	78
CO_3^{-2}	mg/l	0	24	0	0	0	0	0	0
Cl^-	mg/l	13 ± 5	37	10	10	22	6.6	7.4	9.5
CN^-	mg/l	0.00 - 0.01	0.43	7.0	48	0.14	4.0	5.0	0.01
Fe diss.	µg/l	0 - 10	30	380	37000	1700	4400	18000	160
Pb^{+2}	µg/l	0 - 1	1	2	0	0	2	2	7
Li^+	mg/l	34 ± 5	310	30	50	190	50	50	50
Mg^{+2}	mg/l	10 ± 4	19	8.1	28	55	26	26	18
NH_4^+ as N	mg/l	0.55 ± 0.05	19	0.49	2.1	20	0.80	0.77	0.84
NO_2 as N	mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO_3 as N	mg/l	0.02 ± .01	0.01	0.19	0.01	0.07	0.01	0.01	0.02
Phenols	µg/l	1 ± 1	41	15	1000	340	83	15	2
K^+	mg/l	5.4 ± 0.5	57	4.3	7.5	25	7.7	7.7	6.1
Diss. Solids	mg/l	703 ± 70	3390	699	989	2020	1170	1240	1050
Na^+	mg/l	214 ± 15	320	240	350	310	330	320	310
SO^{-2}	mg/l	154 ± 80	2200	37	67	1000	250	320	310
S^{-2}	mg/l	0.3 ± 0.2	4.0	0.7	1.1	—	0.3	2.6	0.6
Zn^{+2}	µg/l	224 ± 200	10	50	20	1200	120	30	20
CH_4	mg/l	11.5 ± 4	1.8	<0.2	0.4	—	<0.2	35.0	—

[a]The ± values indicate the approximate range of the results for the seven baseline wells.

Ignition took place October 15, 1976 and gasification continued for approximately 11 days. During that period, nearly 130 tons of coal were gasified, producing 19 MMSCF of gas (13.2 MMSCF dry) having an average heating value of 110 Btu/scf (1,2). On the seventh day of gasification, water samples were pumped from several of the wells outside the gasification burn boundary. Data from the analysis of two samples (DW-1 and EM-1) are summarized in Table 1 and compared with conditions prior to and following gasification.

It is interesting to note that although gasification had proceeded for only seven days at the time of this sampling, the gasification process had begun to affect the water quality at distances up to 100 feet from the burn zone. In particular, large increases in CN^-, phenols and electrical conductivity were observed.

Although the total amount of DOC also increased during gasification, the distribution of DOC (as determined from fractionation measurements) remained approximately the same as that observed in the baseline study[10]. The concentration of methane present in the water dropped from 11 mg/l to below detectable limits (<0.2 mg/l) in all the wells monitored. Thus, the amount of dissolved CH_4 in the water appears to be very sensitive to perturbations of the natural ground-water system.

Post-Gasification

Water sampling at the Hoe Creek site was carried out at periods of 3, 83, 182 and 280 days following gasification. (Only part of the data are currently available for the most recent (280-day) sampling expedition.) Shown in Table 1 are typical analyses for inside (Injection Well) and outside (DW-1 and EM-1) the burn-boundary. Complete data for all other wells are given elsewhere[10]. Data for some of the contaminants and characteristics showing large changes following gasification have been plotted as a function of distance from the burn-boundary (Figure 4-7). This method of displaying the data implies that the initial release of contaminants is independent of direction (cylindrical symmetry). This is not exactly true, of course, but the results suggest that it is a useful simplification. The assumption of cylindrical symmetry appears to be quite valid for the wells in the close proximity to the burn boundary (i.e., the DW wells), but at large radial distances (the outermost EM wells) the data suggest that the contaminants move more easily in the direction of highest permeability (N59E, See Fig. 1)[4].

Electrical Conductivity, Temperature and pH

An increase in electrical conductivity is a good measure of the increase in ionic species as a result of gasification. Our results show approximately a 2-fold increase in conductivity within 10 feet of the burn boundary, with a rapid drop off to nearly baseline values at a distance of 100 ft (Fig. 4). Also, there is a continuing drop in conductivity between the 83 and 280-day sampling period. As will be shown later, this may be an indication of contaminant sorption by the coal. Inside the burn boundary, the soluble coal ash species produce a highly conductive solution (3500 μmho/cm).

As might be expected, the total dissolved solids (TDS, the residue at 180°C) follows closely the changes observed in electrical conductivity. The TDS level decreases from ~2000 mg/l at 10 ft from the burn boundary to ~900 mg/l at 100 ft. Inside the gasified zone, TDS reaches a value near 3400 mg/l.

The measured temperature gradient near the gasifier was quite large 3 days after gasification (Fig. 4). After 83 days, the system had evolved to a rather slowly varying state with a much smaller temperature gradient. This approach to thermal equilibrium is probably driven by convection near the gasification site. In a later section, it is shown that the mixing caused by convection produces a rather large change in the near-gasifier contaminant distribution immediately following gasification.

The pH of the water remains near 7.0 at points sampled outside the burn boundary. Inside the burn zone, the dissolution of metal oxides remaining in the ash produces a high pH solution (~10 - 10.5). This observed pH value is very close to that predicted by our recent laboratory ash-leaching experiments (see next section and ref. 9).

The measured alkalinity of the water at first appears to contradict the observed pH values: inside the burn zone, the alkalinity is lower (60 mg/l) than it is outside the burn zone (400-600 mg/l). This apparent contradiction results from the fact that whereas pH is a measure of a specific ion concentration (H^+or OH^-), alkalinity is a measure of the ability to neutralize acids, and hence includes not only OH^- but also such species as HCO_3^- and CO_3^{-2}. The alkalinity of water samples taken outside the burn zone is almost totally due to the presence of high concentrations of bicarbonate ion. Inside the gasification zone, only OH^- and CO_3^{-2} contribute to the alkalinity and, because they are present in much lower molar concentrations, they produce a much lower alkalinity (Table 1).

Cation Species

The concentrations of many of the cation species — particularly Mg^{+2}, Ca^{+2}, Li^{+1}, NH_4^+, and K^+ — increased as a result of the gasification process. The metal ions presumably come from the ash material remaining in the burned-out zone, whereas the observed increases in NH_4^+ probably result from the evolution of NH_3 during the gasification process. Ammonia is a commonly observed coal pyrolysis product.

Figures 5 is a plot of Ca^{+2}, Mg^{+2}, K^+ and NH_4^+ concentrations as a function of distance from the gasification boundary for different sampling times following gasification. The fact that log-log or semi-log scales have been used is not meant to imply a particular relationship between concentrations and radius. These scales were chosen simply for convenience in showing a large range of values on a single plot.

The convective mixing that occurs as water re-enters the gasification zone causes a redistribution of soluble ash species into the surrounding coal seam. This accounts for the observed increases in metal ion concentrations which occur between the 3-day and 83-day post-gasification sampling periods (Fig. 5).

The Mg^{+2} concentration is found to be lower inside the burn boundary than it is outside. This apparent anomaly is associated with the suppression of the $Mg(OH)_2$ solubility due to the high pH inside the burn boundary. The solubility product of $Mg(OH)_2$ is 1.2×10^{-11} moles $^3/_{13}$ at 18°C. Hence, a Mg^{+2} concentration of 18 mg/l, as measured inside the burn zone, (Fig. 5) can only exist in a solution of pH $\leq$10.1, which is within experimental error of the measured value (10.3). The higher concentrations of Mg^{+2} that occur outside the burn boundary evidently resulted from mixing at a time when the pH was slightly lower, specifically pH $\leq$ 10.

The variation in concentration with distance observed for other cations (e.g., B^{+3}, Li^+) is quite similar to that shown here for Mg^{+2}, Ca^{+2} and K^+. Furthermore, all species showed the effects of the convective mixing that occurred shortly following gasification.

Other cation species that showed some measurable increases in concentration as a result of gasification are Al^{+3}, As^{+3} and Ba^{+2}. In general, however, only a few close-in wells showed increases in these species.

Aluminum was detected at above baseline levels (220 µg/l) only inside the burn zone. This agrees with laboratory experiments, which showed that aluminum is very strongly adsorbed by coal[3]. Hence, any Al^{+3} swept out from the burn zone into the coal bed would be expected to be quickly adsorbed.

Arsenic showed an increase in concentration inside the burn zone (8 mg/l) and 2 ft outside (DW-4, 21 mg/l); all other wells remained at baseline levels.

Barium was observed at above-baseline concentrations in well DW-4 immediately following gasification (i.e., during the 3-day post-gasification sampling). It was not detected, however, during the post-gasification sampling 83 days later. This is quite reasonable, since the SO_4^{-2} concentration had increased approximately 5 - 20 fold and Ba^{+2} is probably precipitated as $BaSO_4$ (Ksp = 1.0×10^{-10} moles ^{2}/liter^2 at 18°C). Post-gasification analyses showed no significant increase in heavy metals as a result of gasification. In particular, no large increase in lead or mercury was detected[10].

Anion Species

The anions included in the analyses are listed in Table 1. Large increases in concentration were observed for SO_4^{-2} and CN^- (Fig. 6). Bromide ion also increased and in general showed the same behavior as SO_4^{-2}.

The ash bed is the major source of increased SO_4^{-2} and Br^-. The observed increase in SO_4^{-2} concentration between 3 days and 83 days following gasification (Fig. 6) probably also results from the mixing induced by convection shortly following the process.

CN^- was observed in very high concentrations immediately following gasification (3 days). However, by 83 days after gasification, the concentration had dropped approximately three orders of magnitude, reaching background levels at 100 ft from the burn zone. Subsequent analyses (182 and 280 days) have shown a continuing drop in CN^- concentration. It is probable that CN^- is being adsorbed by the coal. Laboratory experiments are currently under way to examine the magnitude of CN^- sorption by coal.

Increased concentrations of nitrates and nitrites were not observed during the post-gasification sampling.

Phenols and other Organic Materials

The measured post-gasification distribution of phenolic materials is plotted in Figure 7. The highest concentration observed was 450 mg/l, three days following gasification at a distance of 2 ft from the burn boundary (well DW-4). The concentration falls off very sharply with radius. Inside the burn zone, the phenolic concentration is only 0.041 mg/l (Table 1).

Also plotted in Figure 7, are data from the 83, 182, and 280-day post-gasification sampling periods. The concentration of phenols has decreased approximately one order of magnitude over the 182 days since gasification. The drop in concentration of phenolic materials is probably the result of sorption by the coal[3,9]. The dissolved organic carbon analyses showed the same general trend observed for the phenolic material — wells close to the burn boundary had much higher DOC levels. Fractionation of the DOC into hydrophobic and hydrophilic groups of acids, bases and neutrals is discussed in more detail in refs. 4 and 10.

Many of the water samples obtained at Hoe Creek were analyzed for volatile and semi-volatile organics using GCMS. Analysis for volatile organics in post-gasification water samples shows an abundance of lower molecular weight polyaromatic and substituted aromatic compounds. As many as 200 different

Table 2. Comparison of laboratory and field measurements of various contaminants originating from ash.

Characteristic	Field measurements (83d) (sampling well in ash bed)	Laboratory Leaching Expts 1000°C	1100°C	1200°C
Ca^{+2} (ppm)	570	645	630	411
Na^{+} (ppm)	320	207	196	193
K^{+} (ppm)	57	9.7	8.9	7.7
Fe^{+3} (ppm)	.030	<.5	—	—
Al^{+3} (ppm)	.220	33	3.9	<.50
Mg^{+2}[a] (ppm)	19.0	(26.0)	(35)	62
Ba^{+2} (ppm)	0	<2.0	—	—
SO_4^{-2} (ppm)	2200	2193	2010	1667
pH	10-10.5	10-11	10.5	7.5-8.0
Conductivity (μmho/cm)	3500	3450	3100	2850

[a] See discussion in text concerning Mg^{+2} solubility at high pH.

species (not detected in the pre-gasification samples) have been quantitatively identified in the water wells close to the gasification zone.

A comparison of the volatile species in the product tar with those found in the water show some similarities. These similarities are best demonstrated when the chromatograms of two water samples- one approximately 45 feet from the burn, and another 5 feet from the burn — are compared with a chromatogram of the product tar. The results show the marked decrease in high-boiling, high-molecular-weight material at points further from the gasification zone. In particular, the concentration of xylenes, other substituted benzenes, indenes indans, and napthalenes is observed to decrease significantly at the greater distance from the gasification zone. The reader is refered to references 4, 8 and 10 for more details on the GCMS analysis of these water samples.

B. Laboratory Ash Leaching and Phenol Transport Experiments

Details of a series of experiments dealing with coal ash leaching and transport of pollutants near an in-situ gasifier are given in Ref. 9. In this paper we summarize some of the important results of that work which relate to the above field measurements.

Ash Leaching

Subbutuminous coal ash samples heat treated to 1000, 1100 and 1200°C were water leached and the leachate analyzed for Ca^{+2}, SO_4^{-2}, Al^{+3}, Fe^{+3}, Ba^{+2}, Mg^{+2}, K^{+}, Na^{+} and OH^{-}. The laboratory results are compared with the cation and anion concentration data from the field measurements in Table 2. Except for K^{+} and Al^{+3} the agreement between the laboratory and field data is excellent. This good correlation suggests that plume dispersion calculations(3) carried out using laboratory leaching data for input may be able to accurately predict

pollutant transport from an underground gasification site. Currently experiments are in progress to generate further laboratory data that can be used in modeling post-gasification plume development.

Phenol Transport Through Coal

Phenolic materials are one of the major organic pollutants associated with in-situ coal gasification. Maximum levels of near 500 ppm have been measured in the groundwater (Fig. 7). Transport of these material away from the gasification site pose a potential long term pollution hazard (Fig. 2).

We have studied the transport of a 600 ppm phenol solution through a column of subituminous coal and measured the absorption of the material on the coal matrix (Fig. 8). The flow rate was 101 m/yr and the distribution coefficient (K_d) was calculated to be approximately 40. This very strong adsorption of phenol on coal is in agreement with static experiments (K_d = 30-40) and with field observations (See Fig. 7). It was also found that the movement of the phenolic solution through the coal column is accurately predicted using a one-dimensional transport model. Results from these and other transport experiments are given in ref. 9.

Acknowledgments

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REFERENCES

1. R. W. Hill and C. B. Thorsness, "Results from an In Situ Coal Gasification Experiment Involving Explosive Fracturing: Hoe Creek Experiment No. 1", Lawrence Livermore Laboratory, Rept. UCRL-52229, (1977).

2. C. Thorsness, R. Hill and D. Stephens, "Preliminary Results from an In-Situ Coal Gasification Experiment Using Explosive Fracturing", Division of Fuel Chemistry, American Chem. Soc. Preprints, 22, 1 (1977).

3. J. H. Campbell and H. Washington "Preliminary Laboratory and Modeling Studies on the Environmental Impact of In-Situ coal Gasification" Proceedings of the Second Underground Coal Gasification Symposium, Morgantown Energy Research Center, Morgantown, West Virginia, (1976) p. 119.

4. S. Warren Mead, John H. Campbell, and Douglas R. Stephens "Ground-Water Quality Effects of an Underground Coal Gasification Experiment" 3rd Annual Underground Coal Conversion Symposium, Lawrence Livermore Laboratory, Livermore, California, (1977), Rept. UCRL-79867.

5. E. Brown, M. W. Skougstad, and M. J. Fishman, "Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases", Techniques of Water-Resources Investigation of the U. S. Geological Survey, Chapter A-1, U. S. Department of Interior, 1970.

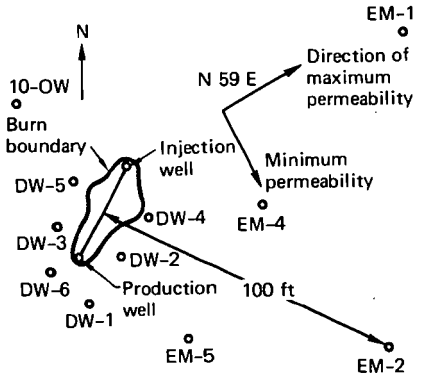
6. D. R. Goerlitz and E. Brown, "Methods for Analysis of Organic Substances in Water", Techniques of Water-Resources Investigation of the U. S. Geological Survey, Chapter A-3, U. S. Department of Interior, 1972.

7. "Water Analysis Handbook" Hach Chemical Company, Ames, Iowa, 1976 edition.

8. E. D. Pellizzari, "Identification of Components of Energy-Related Wastes and Effluents", Research Triangle Institute Rept., Research Triangle Park, North Carolina (1977).

9. V. A. Dalton and J. H. Campbell "Laboratory Measurements of Groundwater Leaching and Transport of Pollutants Produced During Underground Coal Gasification", Lawrence Livermore Laboratory, Rept. UCRL (in press) 1977.

10. J. H. Campbell, J. Busby, S. Santor and W. Mead "Effects of the Hoe Creek I Underground Coal Gasification Experiment on Ground Water Quality", Lawrence Livermore Laboratory, Livermore, CA, Rept. UCRL (in press) 1977.



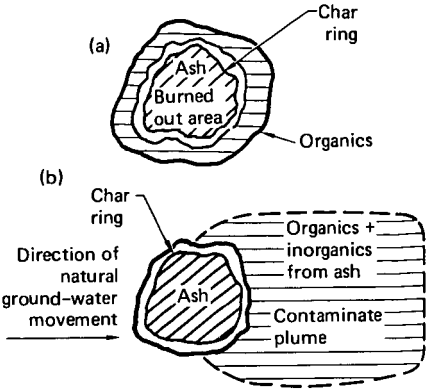


Fig. 2. Plan view of post-gasification burn region (a) and the plume that develops as a result of ground-water flow (b).

Fig. 1. Wells used for water sampling at the Hoe Creek Site.

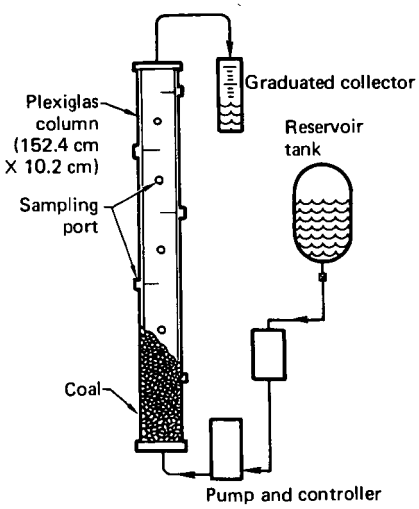


Fig. 3. Schematic of coal column apparatus used to simulate flow of contaminated water through coal.

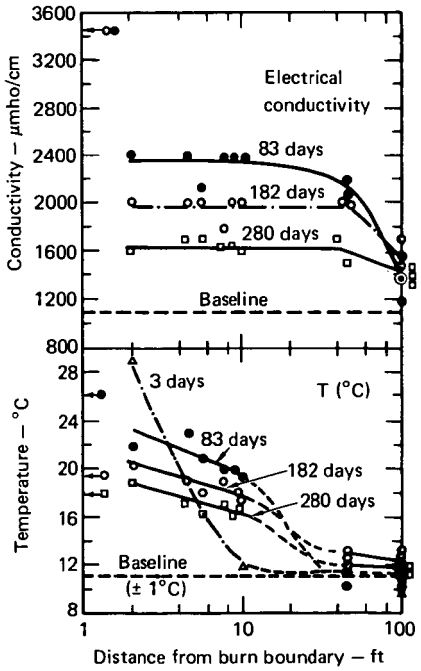


Fig. 4. Electrical conductivity and temperature as a function of distance from the gasification burn boundary. The arrows near the ordinate indicate values measured inside the burn boundary.

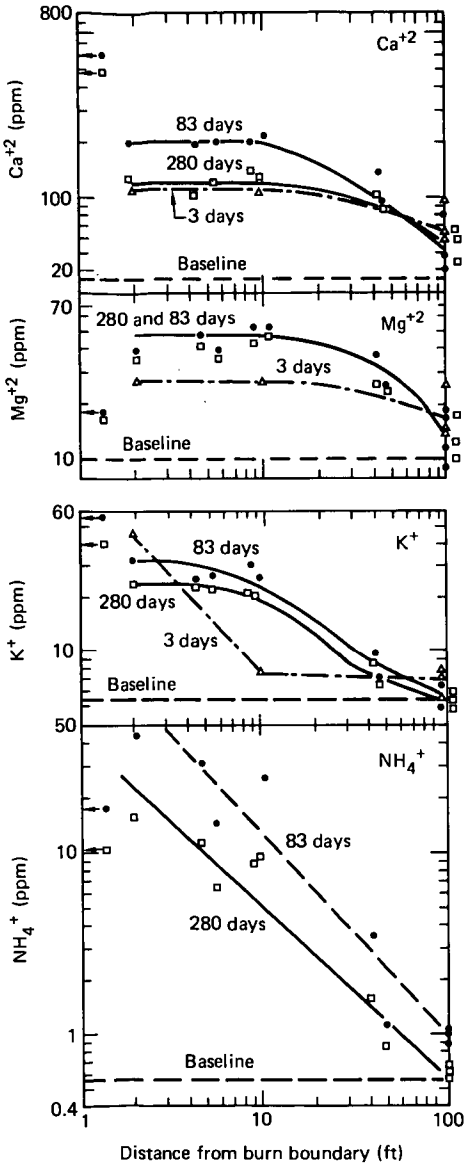


Fig. 5. Concentration of Ca^{+2}, Mg^{+2}, NH_4^+ and K^+ as a function of distance from the gasification burn boundary. The arrows near the ordinate represent values inside the burn boundary.

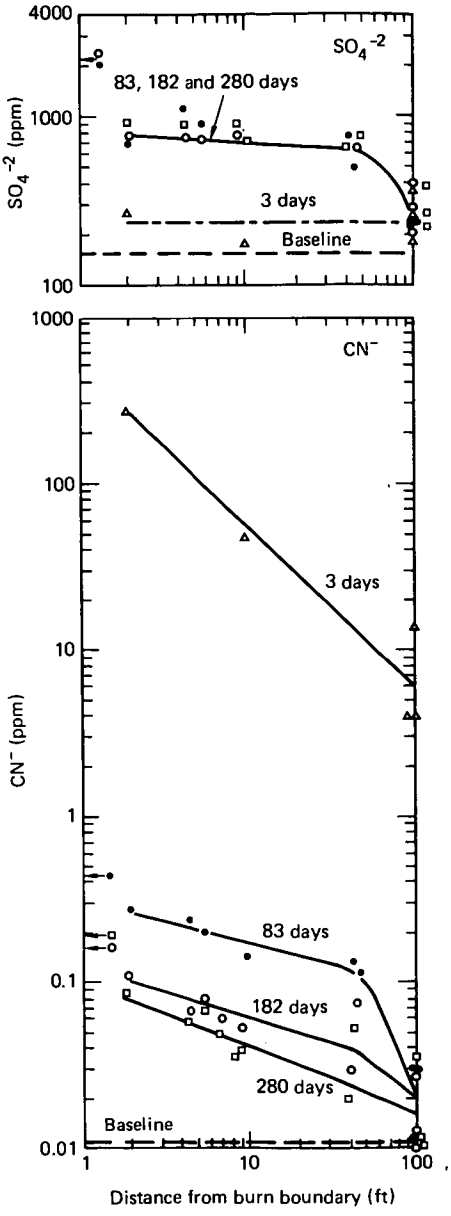


Fig. 6. Cyanide and sulfate concentration as a function of distance from the gasification burn boundary. The arrows near the ordinate represent values inside the burn boundary.

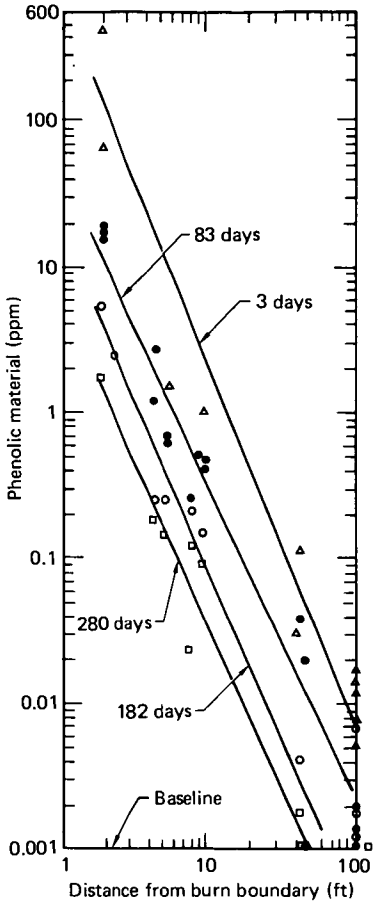


Fig. 7. Concentration of phenolic material as a function of distance from the burn boundary.

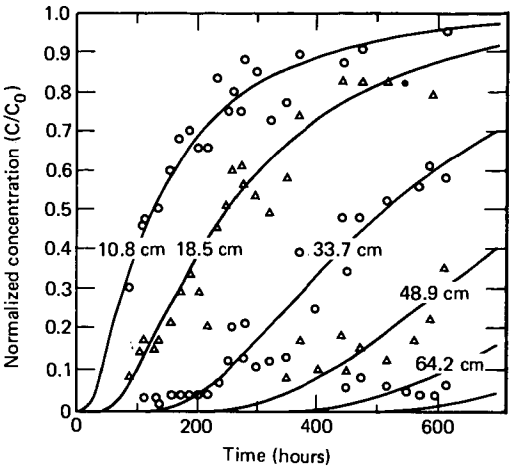


Fig. 8. Phenol breakthrough curves calculated (–) and measured at various distances (shown on figure) along a 1.5 m packed column of subbituminous coal. The coal column is shown in Fig. 3. The concentration of the phenol solution was 600 ppm; the solution was pumped through the column at a linear velocity of 101 m/yr. The average particle size of the coal was 0.71 cm. Further details are given in the text and in ref 9.